Renewable and Sustainable Energy Reviews 21 (2013) 142–152

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Current utilization of microturbines as a part of a hybrid system in distributed generation technology

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ARTICLE INFO

Article history:
Received 17 February 2012
Received in revised form
4 December 2012
Accepted 9 December 2012
Available online 26 January 2013

Keywords:
Microturbine
Hybrid system
Distributed generation
Cogeneration
Fuel consumption

ABSTRACT

Microturbines are a relatively new distributed generation technology. Combined heat and power, known as cogeneration, can be considered the most economical attractive investment in microturbines. Latest technologies and increasing energy prices are propelling this technology to the forefront. This study aims to review the current state of utilization of microturbines in distributed generation as a standalone system or within a hybrid system to supply loads. It is found that more research and development effort is needed to improve the performance of microturbines, integrate them with other energy sources and adopt standards and regulations to connect them with the utility grid. These standards shall be developed to serve all parties and take into account regional and international requirements. Furthermore, complete mathematical modeling, especially for fuel consumption is still required. The development of small scale units within the range of kilowatts for in-house use as a backup source of residential PV system is also needed.

Contents

1. Introduction

Distributed energy resources refer to small generating units that are installed and interconnected to the electric power distribution system near load locations. They are not commonly connected to a bulk power transmission system. Distributed generation typically includes renewable generation and fossil-fuel, as well as energy storage technologies. Distributed energy resources are generally more efficient, since they are located at customer load sites, rendering transmission and distribution system losses less compared to the central station generators [1–3].

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http://dx.doi.org/10.1016/j.rser.2012.12.006

Nomenclature

FCC	fuel consumption cost (€/h)
P	active power (kW)

Abbreviations

Btu	British thermal unit
GAST	gas turbine
G8	group of eight countries
HHV	higher heating value
kW he	electrical kW h
LHV	lower heating value
NO_x	nitrogen oxide gases
P–Q	active power–reactive power
PV	photovoltaic
SO_x	sulfur oxide gases
V–f	voltage–frequency

Distributed generation is expected to play an important role in electricity generation in the near future. The transition from central generation that requires long transmission and distribution networks into distributed generation has gradually taken its place as a result of deregulation of electric utility and energy environment considerations[4]. Microturbine-generation is currently attracting a lot of interest in the distributed generation market to meet user needs of electricity. They can be considered one of the main sources in the field of distributed generation [5–9].

Microturbines are a relatively new distributed generation technology. They are small, compact, contains high speed combustion turbines with outputs ranging from 25 kW to 500 kW [10–13]. They are commonly being used for stationary energy generation applications, as they produce both heat and electricity on a relatively small scale. The microturbine provides input mechanical energy in the form of high speed rotation to the generator, and generator, in turn converts it to electrical energy [14].

Distributed generation using microturbines is a typical solution for standalone, on site applications remote from power grids. Other applications are cogeneration (combined heat and power generation), peak shaving, standby power generation, reliability increase, power boost capacity, cost of energy decrease, and pollutant emission reduction [6,14–20].

Microturbines offer many advantages compared to other technologies, including long life time (about 45,000 h), lightweight, small size, a small number of moving parts, fast response, greater efficiency, lower emissions, lower electricity costs, higher flexibility and opportunities to utilize waste fuels with less noise compared with reciprocating engines[1,6,14,16,21]. Because of their relatively low capital costs, small size, expected low operation and maintenance costs, microturbines are expected to take a significant share of the distributed generation market. Besides, microturbines offer a clean and efficient solution for direct mechanically driven markets, such as air-conditioning and air compression [22].

Microturbines are well suited for small commercial building such as: small offices, restaurants, retail stores, hotels/motels, hospitals and small industries [11,23]. Currently, vested interest in microturbine development involves hybrid vehicles. Other ongoing developments to enhance microturbine features are to use it within a hybrid system that includes other renewable sources. Compared to a diesel generator, microturbines have more fuel flexibility, more reliability, less maintenance, less noise and less pollution [3].

Today's microturbines technology is the result of development work beginning in the 1950s. Much of this work was done by the automotive industry [24]. Microturbines began initial service in 1999–2000. Table 1 summarizes different stages of development that microturbines passed through and the future expectations for this technology [7,15,20,24–26].

2. Microturbine construction and operation

Microturbines are similar to gas turbines in terms of design. Any microturbine is constructed of the following main parts [4,15]: turbine that transforms pressure of hot gas after it is expanded through it into motion, alternator that generates electricity, compressor that compresses the inlet air to high pressures, combustor at which combustion begins between the heated compressed air and the fuel after they are mixed and burned, recuperator which used as a heat exchanger to transfer

Table 1
Development stages of microturbines.

Year	Microturbine development
1950s	Began research [24]
1988	Capstone turbine corporation began developing the microturbine concept [24]
1997	Entered field testing [24]
1998	Capstone was the first manufacturer offering commercial power products [24]
1999–2000	Entered the commercial market [24]
Late 1990s	Emerged as new on-site power generation technologies [7].
2000	Projected to find acceptance in large quantities in the distributed power generation field [20]
2000	Electrical efficiency=23–30%, Overall efficiency=65–75%, Installed cost=1050–1300 Euro/kW, O&M costs=0.5–1 C/kW h, NO_x (kg/MW h) <0.217* [15]
2003	Overall efficiency=62%, Installed cost=1040 Euro/kW, O&M costs=1.2 C/kW h*. For 100 kW microturbine [25]
2010-expected	Electrical efficiency=38–42%, Overall efficiency=70–80%, Installed cost=550–850 Euro/kW, O&M costs=0.1–0.2 C/kW h, NO_x (kg/MW h) <0.217* [15]
2020-expected	Electrical efficiency=36%, Overall efficiency=82%, Installed cost=700 Euro/kW, NO_x (kg/MW h) <0.2*. For 100 kW microturbine [26]

O&M: Operation and maintenance.
C: Euro cent.
* Efficiency calculations are based on the HHV of the fuel.

heat from the exhaust gas to air before it enters the combustor and power electronics section.

Two types of turbines are present: the single shaft and the split shaft. Table 2 shows a comparison between the two types [4,14,15] while Fig. 1 [27] and Fig. 2 [28] shows schematic diagrams for single shaft microturbine and split shaft microturbine, respectively.

In its operation, the microturbine is similar to any conventional gas turbine. Its operation is based on the Bryton cycle [11,27]. The incoming air enters the compressor; the compressor in turn compresses it to high pressure values. The pressurized air enters to recuperator, where heat is transferred from the exhaust gas to this pressurized air. After that, the heated pressurized air enters, along with the fuel, to the combustion chamber where the burning begins. The result of this is a very hot gas at high pressure and temperature. This pressurized hot gas enters the turbine where it is allowed to expand. This will produce the energy that is used to drive both the alternator and the compressor. The driven alternator generates 3 phase power at high or normal frequencies depending on the type of shaft.

The exhaust gas from the turbine is allowed to pass through a heat exchanger (regenerator) to extract heat and utilize it for different purposes (heating space, boilers, cooling systems, etc.).

The inlet air is filtered before it enters the compressor. In different designs, it is allowed to pass through the alternator and the electronic devices for cooling.

The microturbine can be operated in different modes of operation according to the type and location of application and availability of other sources. It can be operated as a main source to supply certain load for off-grid applications, as a standby source for on-grid applications instead of a diesel generator, or within a hybrid system with other renewable sources for on- or off-grid applications.

3. Microturbine modeling

Modeling of microturbine (thermodynamic behavior) under different modes of operation can be found in different previous research works [2,4,6,12,14,29–32]. These modes include testing the operation of the microturbine under steady state and/or transient (dynamic) state, stand alone or within a hybrid system. The control systems involved in the microturbine system that modeled are temperature control, fuel flow control, speed and acceleration control. The temperature control acts to limit the upper bound of the output power. The fuel flow control section adjusts the amount of fuel entered to the combustion chamber as load changes. The speed control regulates the speed of the microturbine at different load conditions while the acceleration control limits the speed rate during starting up of the microturbine.

The modeling of microturbine concerning fuel consumption and its relation with rated power and output power supplied by it (economic model) can be found in Refs.[12,33–35].

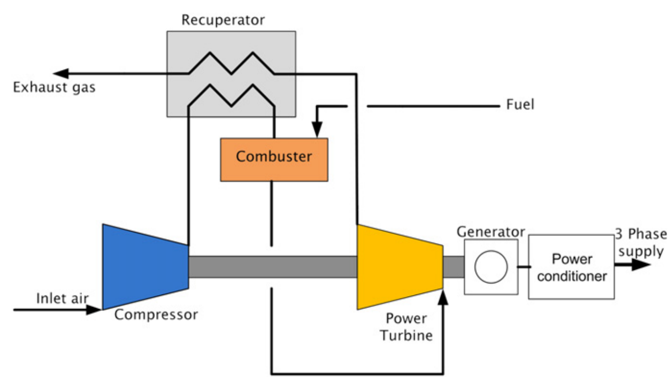


Fig. 1. Schematic diagram of a single shaft microturbine [27].

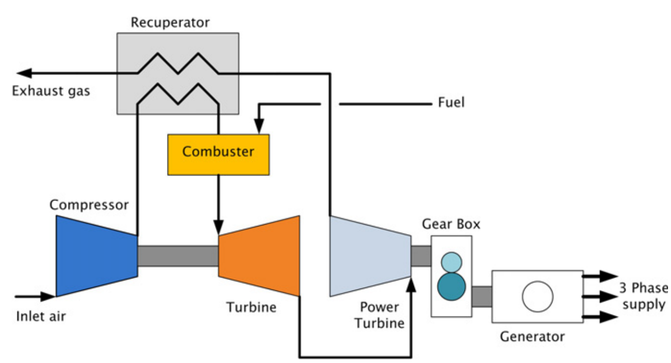


Fig. 2. A schematic diagram for a split-shaft microturbine [28].

Table 2
Comparison between single shaft and split shaft microturbines.

Difference item	Microturbine type	
	Single shaft	Split shaft
Speed of rotation (rpm)	50,000–120,000	3,000 or 3,600
Alternator frequency (Hz)	1,500–4,000	50 or 60
Coupling	Turbine and alternator are directly coupled	Gear box is used to couple turbine shaft with alternator shaft
Power electronics	Power electronics section is needed to convert the high frequency AC output voltage into DC and then into AC with frequency of 50 Hz or 60 Hz.	No need for power electronics
Alternator type	Usually permanent magnet synchronous generator	Usually induction generator
Maintenance	Less maintenance	Higher maintenance because of additional moving parts.
Cost	Usually higher cost because of the power electronics section and type of generator used.	Lower cost
Chances of failure	Higher chances	Lower chances as gearbox is more robust than complex power electronics section.
Dimensions and weight	Lower	Higher because of gearbox and the lubricating system

3.1. Technical modeling

Gaonkar and Patel [6] presented a model based on a slow dynamics of a single shaft gas microturbines, including all control systems under normal operating conditions for isolated applications. Fast dynamics including starting, shutting down, loss of power and internal faults were neglected in their model. Furthermore, a lead lag transfer function was used to represent the speed controller. The results of simulation of their model showed that it is suitable for slow dynamic studies, and at the same time has the ability to adjust in order follow load changes. Fig. 3 illustrates the Simulink implementation for their model, while Fig. 4 illustrates the results of the simulation of this model as the load changes at $t=10$ and 20 s. In their model, the start-up dynamics associated with starting the microturbine as a motor until it reaches its nominal speed before functioning as a generating system were not considered. Besides, the recuperator was not included in their model whereas the recuperator is an essential part of the microturbine system to increase its efficiency. In Ref. [4], the authors presented a dynamic model, assuming that the torque response is a first order system. PSCAD/EMTDC was used to simulate both the microturbine and the power electronics section. In this reference as in Ref. [6], starting period and recuperator modeling were not considered. The results of different simulation tests performed on their model illustrate that this model is suitable for standalone, grid connected, and microgrids. The results also illustrate that their developed model can quickly follow the load variations. Authors of Ref. [14] presented a simplified model of microturbines in their two modes of operation; namely, islanded mode and grid connected mode, with the simulation performed under different load conditions with and without speed controllers. Temperature and acceleration controls and recuperator modeling were not considered in their model where the microturbine was considered to operate under normal conditions. The results of their tests also illustrate that their models are capable of following load demands. Their results were compared with results of other studies and with real data obtained from testing a similar system. In Ref. [2], authors developed a model which is suitable

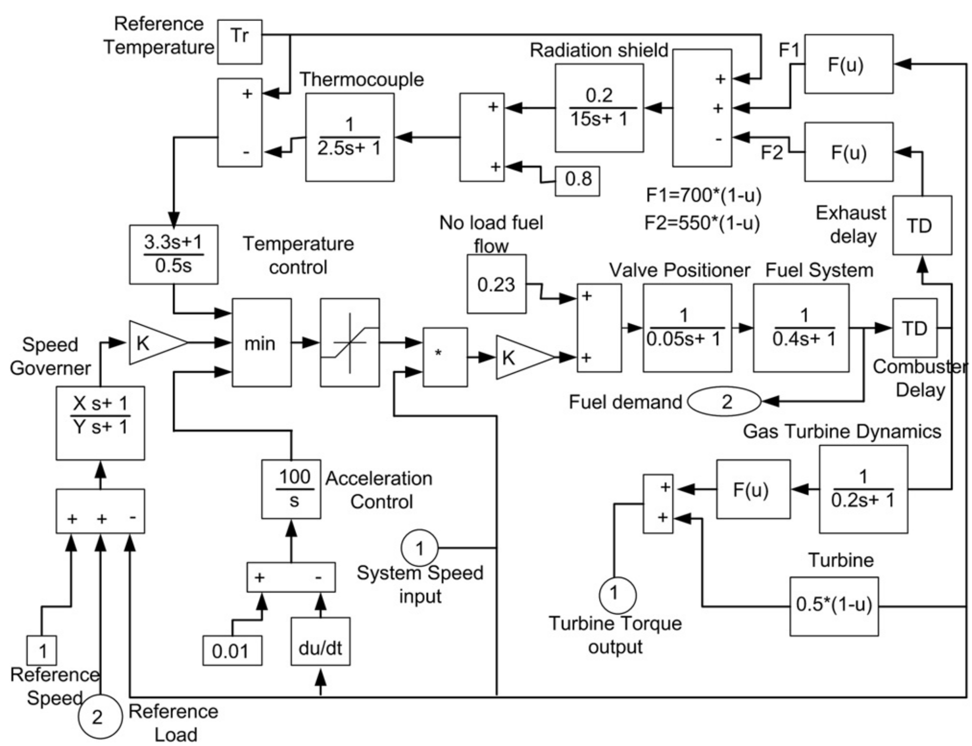


Fig. 3. Simulink implementation of microturbine system [6].

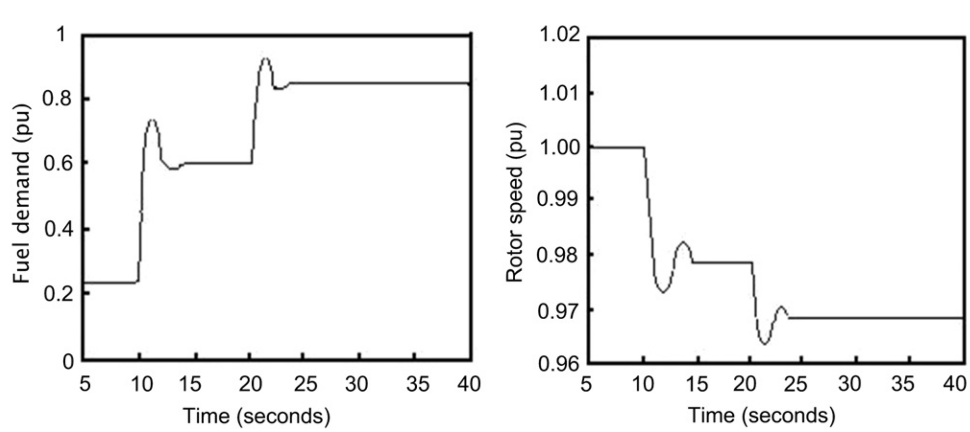


Fig. 4. Results of simulation of the developed model of the microturbine [6].

for driving isolated loads. Besides the microturbine model, they developed the model for the driving system to test its functionality with the microturbine system. Simulink/MATLAB was used to simulate their developed model. Modeling of recuperator was not included in their model. Their simulation results show that the model they developed is appropriately functioning for isolated loads. The authors of Ref. [12] used a model of microturbine that is developed by General Electric. This model is called GAST model, and it is one of the common models used to simulate the behavior of gas turbines under dynamic and steady state operation. The same model was used and tested by the authors of Refs. [36,37]. The purpose of these two studies was to compare response time to reach the steady state between the microturbines and the fuel cells. The results indicate that the microturbine is faster in its response. It has a better capability to follow load changes which makes microturbines are suitable for distributed generation applications. Simulation results also indicate the effectiveness of using GAST model to describe the operation of microturbines. Fig. 5 illustrates the block diagram of this model, involving different required controls [12]. This model can be simplified by omitting part of the controls as temperature control and/or acceleration control [10,14]. In Ref. [31], the authors developed a SIMULINK model for a microturbine as well as for machine side converter controller. The results of their model illustrate its ability to maintain constant speed of microturbine and constant DC voltage at converter output without any disturbance. The reactive power required by the system is obtained by the included LCL filter. This LCL filter also reduces the high order harmonics at the load side. The authors of Ref. [32] developed a mathematical model that includes microturbine, synchronous generator, and all other electronic circuits. Their results show that their model is useful for studying the behavior of microturbines when connected to a low voltage distribution system.

In the previous literature concerning the technical modeling of the microturbine, different models were developed and tested by different researchers. The purpose is to simulate the operation of the microturbine under different conditions, to test the ability of different controllers to maintain the operation within prescribed limits and to investigate the capability of the microturbine to follow load changes with a very short response time. The reviewed results indicate this although some of reviewed references did not take into account temperature and acceleration controls as their effect under slow dynamics and normal operations is so limited. All of the previous reviewed references did not include the recuperator in their models of the microturbine. Its effect on the overall dynamic behavior is limited as it has a slow response time. Furthermore, these references did not consider the starting dynamics associated with starting the microturbine as a motor until it reaches its nominal speed before functioning as a generating system. These starting dynamics are very important for the microturbine and need to be carefully investigated in future researches.

For the grid connected mode, the P–Q control strategy has been used. In this strategy, the active and reactive powers delivered to the grid are controlled by setting a reference values for each of them. Furthermore, the DC rectified voltage in the power electronics section is regulated at a certain set value. For the islanded (off-grid) mode, the V–f control strategy has been used. In this strategy, the output AC voltage and frequency are regulated at desired values for each of them. For the dual mode operation, the two control strategies shall be considered to ensure proper operation of the microturbine.

3.2. Economical modeling

Kalantar and Mousavi [12] suggested a method to model the fuel cost function of microturbines. Their model depends on the fact that the data related to the fuel consumption with output power is known from the manufacturer. They suggested a second order equation to model this fuel cost function. The coefficients of this equation can be determined using least square estimation algorithms depending on the clarified points of this fuel cost curve as function of output power.

Alkhalil et al. [33] depended on data measurements taken for the Capstone model C30 microturbine operating on natural gas fuel. These measurements are for fuel flow in (Btu/h) for different loadings supplied by the microturbine. The power of these loads ranges from 2 kW to 30 kW. Their results indicate that the relation is approximately linear. Using MS-EXCEL, they constructed another curve relating fuel consumption cost (*FCC*) in (€/h) and the load power (*P*) in (kW).They found a trend in this

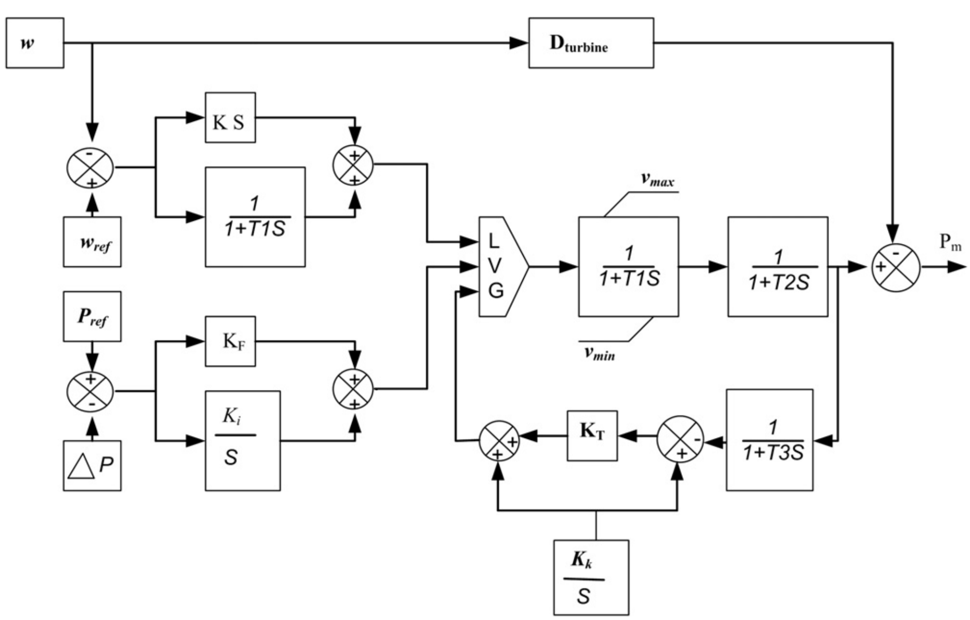


Fig. 5. GAST model of the microturbine [12].

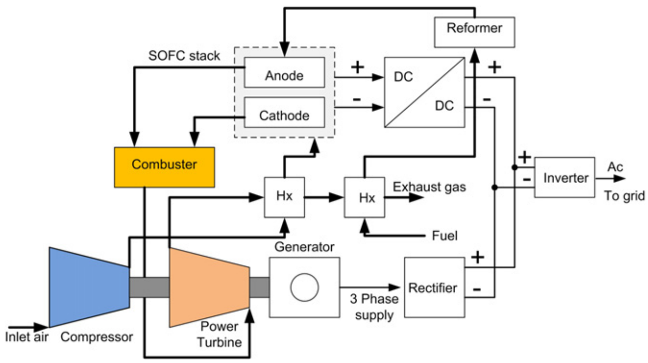


Fig. 6. Fuel cell–microturbine hybrid system [38].

reconstructed curve, represented by the quadratic equation as follows:

$$FCC = 0.0005 \times P^2 + 0.1809 \times P + 1.223 \quad (1)$$

where $1\ \text{Btu} = 293 \times 10^{-6}\ \text{kW h}$ conversion factor and 0.0597 €/kW h for natural gas price are taken into account to reconstruct this curve.

This mathematical model is special for C30 Capstone microturbines with the natural gas price as mentioned. This model can be generalized for C30 model considering unknown prices of natural gas. Furthermore, it can be generalized for other ratings of microturbines by just multiplying it with a rating scale factor. This is due to the fact that the curves for different microturbine ratings have approximately the same trend.

Rahman and Pipattanasomporn [35] depended on a curve relating the efficiency of a 30 kW microturbine with the corresponding output power. They sectionalized the curve into three linear sections, and construct an equation for each section relating electrical efficiency to output power. At any output power, one can find the corresponding efficiency, and determine the corresponding input power in kW h/h. From this input power, one can find the amount of Btu/h and depending on LHV of natural gas, the amount of fuel in kg or m^3 per hour can be found.

All the reviewed references concerning microturbine fuel consumption modeling depended on the manufacturer data to obtain a relation between the fuel consumption and the output power. The fuel consumption model is a microturbine specific charecteristic. Depending on the available datafrom the microturbine manufacturer, the user shall develop the appropriate mathematical model that can be used for further microturbine applications studies. For the cases where the fuel consumption data are not available, one can depend on a generelized developed mathematical model relating the fuel consumption with the output power.

4. Modes of operation of microturbines

As previously mentioned, microturbines can be operated as a standalone source to supply base loads. For grid connected applications, they can be operated as standby or peak shaving sources. Microturbines can be operated within a hybrid system with other sources. For this case, they can be operated as a main source or a standby source. A hybrid system which consists of a combination of more than one type of generation sources can utilize the best operating features of these sources. For most cases, they achieve higher efficiencies compared to single sources [38,39].

4.1. Hybridization microturbine with fuel cells

This mode of operation was analyzed by different research works [4,38,40,41]. Mohamed et al. [4] introduced a study of a microturbine with fuel cells to work as a standalone or to be connected to a micro grid. The results of their developed model simulation illustrate how the load is distributed between the two sources in both modes of operation. Their results showed the feasibility of using microturbine and fuel cells as distributed generation sources in a microgrid. Both microturbine and fuel cell can quickly regulate their outputs to meet the load variation. Part of the study involved in Ref. [38] concerns analyzing the operation of solid oxide fuel cell with microturbine. Both sources are tightly coupled in thermodynamic cycles with each other. Fig. 6 shows the two sources, coupled to the same thermodynamic cycle [38], and the simulation results show that this will improve features and increase the efficiency of both sources in comparison with the operation of each separately. According to the location and application of this proposed hybrid system, different types of fuels can be used. Martín et al. [40] presented a hybrid system consisting of solid oxide fuel cell with gas microturbine. The electrical efficiency of the solid oxide fuel cell increases as a result of hybridization with microturbine. Furthermore, the high temperatures of the exhaust gases can be utilized to activate the trigeneration systems that involve absorption chiller cooling. The electrical efficiency of the microturbine will also increase, because the emitted exhaust gases from solid oxide fuel cell are burned in the combustion chamber of the microturbine. They also concluded that this system will decrease emissions and provide security of supply. They summarized different possibilities of microturbine integration with other types of energy supplies and storage systems. Komatsu et al. [41] analyzed the performance of a hybrid system constructed of fuel cell and a micro gas turbine. In their study, they concluded that using this hybrid system will lead to higher efficient operations, and these higher efficiency values can be maintained even if the system operates at partial load.

According to the previous literature review concerning hybridization microturbine with fuel cells, the operation of the two sources when coupled to the same thermodynamic cycle will increase the efficiency of both. This will also improve features of both depending on the fact that different types of fuels can be used and the high exhaust temperatures can be utilized for cogeneration purposes. For separate operation within the same distributed generation system, the two sources can quickly follow load changes but microturbines respond faster than fuel cells. Storage devices are needed to compensate for this power mismatch when fuel cells are operated in standalone modes while using microturbines to operate in parallel with the fuel cells can help in reducing this need.

4.2. Hybridization microturbine with other renewable sources

Kalantar and Mousavi [12] proposed a hybrid system consisting of wind turbine, microturbine, solar array and battery storage to supply an isolated load far from utility networks. In addition to dynamic modeling of different components constructing this hybrid system, optimal sizing of these components for economical and efficient utilization was accomplished. Energy management between different sources was controlled by a suggested supervisory controller. Set points of different controllers were automatically adjusted in order to achieve proper operation of the system under different conditions. Microturbine and battery storage were selected as backup sources for this system. According to the dispatch strategy considered in this study, the priority is to supply load from wind turbine and solar array. Any deficit

can be supplied by the battery and the microturbine. Mousavi [42] proposed in a similar study a hybrid system consisting of wind turbine, tidal turbine, microturbine and storage battery to supply offshore loads. The same methodology used in [12] was used in this study and the results of both studies indicate the capability of such systems to effectively supply isolated loads. In Ref. [43], the evaluation of using PV and combined heat and power (not micro turbine) as a hybrid system for residential applications is performed. This study concludes that adopting this system will enhance PV penetration level as an electricity source for different applications. In this case, the combined heat and power source acts as a standby supply to match the PV output during the day and at the same time a source for heat when it is in the run mode. The results of this study can be generalized for microturbines when operated for cogeneration purposes. In Ref. [44], the authors presented a hybrid system, consisting of wind turbine and a microturbine for standalone applications. A case study depending on actual residential load profile and real wind data was analyzed. Both the wind turbine and the microturbine with all required controls and the power electronics interfaces were modeled in this study. The power dispatch strategy among different sources was also suggested. The system performance was evaluated in this study, and the simulation results indicated the suitability of adopting this type of hybrid systems to supply loads within distributed generation systems. This hybrid system takes advantages of wind energy, while at the same time, minimizes microturbine fuel consumption and keeps a high level of reliability. Mohamed and Koivo [45] presented a multiobjective mesh adaptive direct search approach to minimize the cost and reduce the emissions of a hybrid system consisting of wind turbine, microturbine, diesel generator, PV array, fuel cell and battery storage. A comparison was made between their approach and other optimization approaches. Their presented results ensure the effectiveness of their proposed approach to meet the load demand and minimize the overall cost of the system and its emissions.

The previous reviewed studies concerning hybridization microturbine with renewable sources indicate the ability of microturbine to be integrated with other sources to meet load demand. The use of microturbine as a backup source instead of diesel generator introduces additional benefits for the hybrid system as it is less pollutant emissions and noise generation and more reliability and flexibility to follow load changes. Except the study [43], the other reviewed studies in this subsection dealt only with the electrical output of the microturbine, whereas utilizing the cogeneration (power and heat) feature of the microturbine will surely enhance the mentioned benefits of it within a hybrid system.

4.3. Utilization of microturbine for cogeneration and trigeneration purposes

During power generation, the microturbine simultaneously generates thermal energy. Usually, this thermal energy is dissipated into ambient air. However, some of this waste thermal energy generated in the process of electricity generation can be recovered for further uses. This thermal energy can be directly and totally utilized by thermal loads (cogeneration systems). In cogeneration systems, this thermal energy is totally utilized by thermal load, while in trigeneration systems, part of it can be utilized by absorption chillers for cooling purposes. Fig. 7 shows a schematic diagram of a microturbine in a combined power and heat (cogeneration) application, while a schematic diagram for a trigeneration system is shown in Fig. 8.

Smolen and Budnik-Rodz [46] evaluated the usage of cogeneration systems with microturbines. In their study, they depended on the fact that the efficiency of microturbines does not considerably

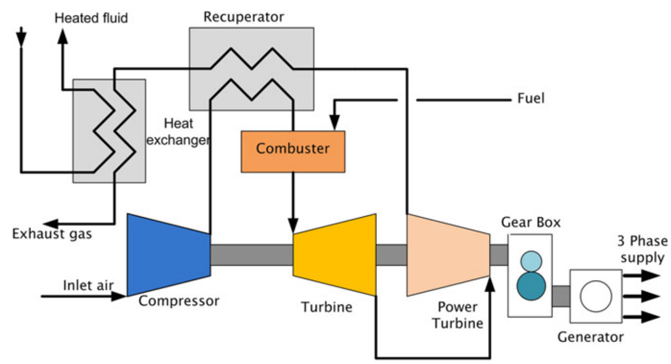


Fig. 7. Schematic diagram of a microturbine cogenrative system [10].

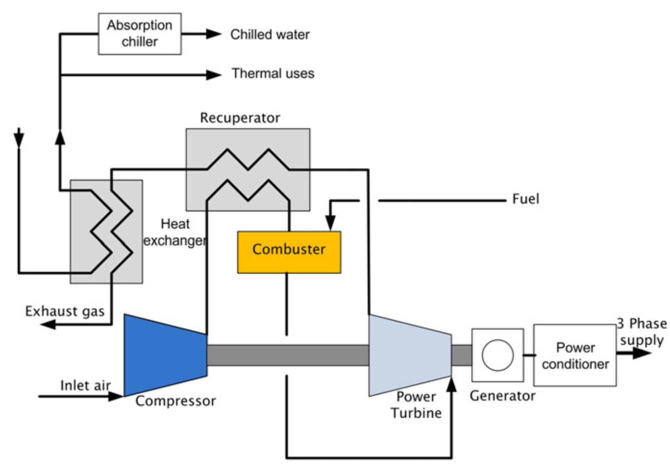


Fig. 8. Microturbine in combined power and heat application [27].

change with load variation, especially for loads greater than 50% of the full load. For the purpose of their study, its value is considered constant. A real case was analyzed to study the feasibility of using microturbine for cogeneration purposes (with and without cooling). From their study, the cost-effectiveness of utilization of microturbines for cogeneration purposes is proven. They concluded that although the cost effectiveness appears for both cases of analysis(-with and without cooling), the most effective option is the option without cooling. In Ref. [47], the authors presented a daily simulation model to analyze the operation of natural gas microturbine for residential applications. In their study, two configurations were analyzed. In the first configuration, the system is tailored to meet the thermal demand of the load, while in the other configuration; the system is tailored to meet the electrical demand of the load. They concluded that for the first configuration, there is a need to buy electricity from the grid, while for the second configuration; the excess in thermal energy is released to the atmosphere. They concluded that an economic analysis shall be done to compare the two options and therefore the optimal choice will be chosen.

Interest in combined heat and power technologies has increased over the past years. The combined heat and power systems have a potential for different residential, commercial and industrial applications. The different generation technologies can provide both heat and power in their generation processes. In Ref. [26], different graphs and tables were presented for comparison purposes between different technologies that provides combined heat and power. Table 3 summarizes part of their results that compare between these different technologies with regard to costs and efficiencies. This comparison was done on the basis of actual data in year 2002, and expected data in year 2020.

Table 3
Costs and efficiencies of different generation technologies.

Technology	Data 2002			Expected data 2020		
	Price ($/kW) ($1999)	Electrical efficiency* (%)	Thermal efficiency* (%)	Price ($/kW) ($1999)	Electrical efficiency* (%)	Thermal efficiency* (%)
Microturbine 100 kW	1970	25.7	45	915	36	46
Fuel cells 200 kW	3674	36	58	1433	50	49
Combustion turbine (1 MW)	1600	21.9	64	1340	28	63
Combustion turbine (10 MW)	965	29	63	830	38	58
Internal combustion engine (100 kW)	1390	28	31	990	31	71

* Efficiency calculations are based on the HHV of the fuel.

Table 4
Recent researches studying integration of microturbines in distributed generation systems.

Reference	Year	Study/domain	Application
[42]	2012	Hybrid system consisting of wind turbine, microturbine, tidal turbine and battery storage; dynamic modeling analysis; optimal sizing; energy management; fuel consumption modeling	Standalone
[45]	2012	Hybrid system consisting of wind turbine, microturbine, diesel generator, PV array, fuel cell and battery storage; size optimization; effectiveness to meet load demand	Microgrid
[12]	2010	Hybrid system consisting of wind turbine, microturbine, solar array and battery storage; dynamic modeling analysis; optimal sizing of different components	Standalone
[40]	2010	Microturbine with solid oxide fuel cell coupled in the same thermodynamic cycle; study of effect of this on global efficiencies and gas emissions of both	Microgrid
[41]	2010	Microturbine with solid oxide fuel cell coupled in the same thermodynamic cycle; study of effect this on efficiency at partial load operation	Standalone
[4]	2009	Microturbine with fuel cell; study of load sharing between the two sources; study of ability to follow load changes	Standalone or micro grid
[43]	2009	Hybrid system consisting of PV and cogeneration system; effect of this on PV penetration and reducing energy waste	Grid-connected
[44]	2009	Hybrid system consisting of wind turbine and microturbine; dynamic modeling; energy dispatch strategy; load sharing between two sources	Standalone
[47]	2007	Microturbine for residential applications; study of its ability to follow thermal and electrical demands; need to purchase electricity from the grid	Grid-connected
[38]	2005	Microturbine with solid oxide fuel cell coupled in the same thermodynamic cycle; study of effect of this on features of both	Standalone
[46]	2005	Cogeneration systems with microturbines; feasibility of using microturbines for cogeneration purposes (with and without cooling); economic analysis	Standalone

The cost-effectiveness of utilizing microturbines for cogeneration systems has been proved according to the previous review. This advantage with other technical and environmental advantages of microturbines shall encourage for more penetration of this technology in different types of applications. As mentioned in the previous subsection, most of research studies focus on the electrical output of the microturbines. Investigating the effectiveness of utilizing the thermal energy requires more research. The additional cost of the cogeneration section and its effect on the total cost, amount of thermal energy generated and its relation with the electrical output are among the issues that shall be addressed in these research studies.

As a summary of this section, Table 4 presents for different reviewed studies concerning hybridization microturbines with different technologies under different modes of operation. Domain and contributions of each are also included in this table.

5. Environmental considerations of operation of microturbines

One of the most important points that enhances the penetration and adoption of microturbines as a main source in distributed generation systems is the environmental concerns. As previously mentioned, one of the attractive benefits of microturbines is its limited emission of pollutants compared to conventional power plants [1,4,11,14,15,22,27,29,33,38,43,44,46–49]. In Refs. [14,15], it is specified that the NO_x emissions are lower than 7 ppm for natural gas microturbines. Medrano et al. [22] presented in a table, the emissions of CO_2 and NO_x gases for different energy sources. For microturbine, it is 0.000318 kg NO_x/kW he and 0.682 kg CO_2/kW he generated. In Ref. [13], a table summarizes NO_x and CO_2 emissions for different generation technologies. Compared to other fossil fuels, the microturbines have the least NO_x emissions, while CO_2 emissions are approximately similar to other sources. The authors of [33] presented different results for the measurements of CO and NO_x emissions for different load levels. In this study, it is concluded that to minimize emissions, it is advantageous to operate microturbine to supply loads in the range 50% to 100% of its rated power. In Refs. [38,43], it was concluded that the importance of involving microturbines within a hybrid system to minimize different emissions. Colombo et al. [50] studied and analyzed emissions of a cogeneration system based on a microturbine. NO_x, SO_2, CO and CO_2 emissions are taken into consideration in this study for different load levels. It was concluded that emission levels depend on output power. Concentrations of SO_2 and CO decrease as the output power increases, while concentrations of NO_x and CO_2 slightly increase as the output power increases. Ref. [51]presents typical values for emissions for different microturbine ratings. For NO_x, the highest concentration registered was 9 ppm (volume basis), and it is for a 28 kW microturbine, for other higher ratings, it takes lower values. Canova et al. [52] concluded that NO_x and CO pollutants emitted as a result of operating microturbines as a combined heat and power unit using natural gas fuel is smaller compared to the case where the heat and electricity are generated separately. This is also applicable for CO_2 pollutant.

Qian et al. [53] analyzed the consideration of environmental effect on the cost of generation. They concluded that a great deal for pollutant emissions has to be paid if environmental costs are considered for traditional fossil-fuel plants. This will make distributed generation, depending on microturbines; compete with large fossil-fuel plants. They also concluded that the development of distributed generation, depending on microturbines or other sources should be accelerated if the environmental value of the pollutant emissions is considered. Gomes et al. [54] obtained their results from experimental tests on microturbines operating at full load and partial loads using natural gas fuel. Their results illustrate that NO_x and CO pollutant emissions are less than 7 ppm (volume basis). This enables implementation of these units among residential and commercial establishments. Their results also show that the highest efficiency is achieved at full load, and remains almost constant until the load is below 50%. The same conclusion appears in [52]. Moreover, according to [52], it is advised by many manufactures to switch off the microturbine unit if the output drops below 50%, where the performance falls rapidly and consistently below this partial load operation.

Ref. [26] presented different graphs for comparison purposes between the different technologies considering gaseous emissions. Table 5 summarizes part of these presented results. In Refs. [51,53], different tables were presented, that summarizes the typical costs and performance characteristics of different combined heat and power technologies. Table 6 presents part of these results.

6. Standards and regulations

The world demands environmentally friendly generation systems. PV panels, wind turbines, microturbines and fuel cells are the most popular environmentally friendly generation sources[39,55,56]. During the G8 Summit in St. Petersburg (2006), the members stated that to reduce global energy security risks, a diversification of the energy mix should be adopted [57]. This calls for different standards and regulations covering different issues. These standards relate safety and performance of the distributed generation products themselves, as well as their connection and synchronism operation with the grid. This, in turn, will facilitate the penetration of new distributed generation into existing distribution networks. These regulations shall be carefully crafted to ensure access to all advantages of distributed generation, and it shall also cover the technical aspects, as well as the economic aspects.

On top of the local benefits that are provided by the distributed generation to its owner, it also offers additional options for utilities, such as there duction in greenhouse emissions, the increase in energy efficiency, the sharing of renewable sources in energy consumption, and the sharing in transport sector. These are the four targets that endorsed by Brussels European Council (March 2007). The increase in the deployment of distributed generation will contribute effectively to achieve these policy goals. Moreover, this will constitute a key element for achieving the three objectives of European energy policy (competitiveness, sustainability and security of supply) [58].

Despite many benefits associated with distributed generation, the integration of distribution to the utility grid may also add to the cost and complexity of grid operation. This complexity depends on the technology, time and site [58].

Martel and Turcotte [59] listed in tables different product standards for new distributed generation systems. The standards are both for domestic and international applications. They also listed the international level standards that regulate installation

Table 5
Gaseous emissions for different generation technologies.

Technology	Emissions (kg/MW h)		
	NO_x	SO_x	CO_2
Recuperated microturbine (100 kW)	0.200	0.004	723.946
Fuel cells (200 kW)	0.014	Neglected	488.981
Large gas turbine (70 MW)	0.268	0.003	581.062
Large gas combined cycle (500 MW)	0.027	0.002	351.994
Catalyst gas-fired rich burn internal combustion engine	0.227	0.003	624.154
Controlled diesel engine	2.132	0.206	649.555

Table 6
Costs and performance characteristics of different generation technologies.

Quantity	Technology				
	Microturbine	Gas turbine	Reciprocating turbine	Steam turbine	Fuel cells
Electrical efficiency* (%) [50]	18–27	22–36	22–40	15–38	30–63
Overall efficiency* (%) [50]	65–75	70–75	70–80	80	55–80
Typical capacity (MW) [50]	0.03–0.25	0.5–250	0.01–5	0.5–250	0.005–2
Installed cost (2007 $/kW) [50]	2400–3000	970–1300	1100–2200	430–1100	5000–6500
Operation and maintenance costs (2007 $/kW h) [50]	0.012–0.025	0.004–0.011	0.009–0.022	<0.005	0.032–0.038
Generation cost (2007 $/kW h) [52]	0.075–0.100	0.045	0.055–0.100	0.045	0.100–0.150
Generation cost considering environmental costs (2007 $/kW h) [52]	0.0785–0.104	0.168	0.0632–0.108	0.168	0.165–0.215
Start-up time [50]	60 s	10 min–1 h	10 s	1 h–1 day	3 h–2 days
NO_x (kg/MW h) [50]	0.023–0.0558	0.0558–0.0776	0.020	0.154–1.86 (according to fuel type)	0.0039–0.0062

* Efficiency calculations are based on the HHV of the fuel.

of distributed generation to the distribution and transmission systems. One of the standards that were adopted by different suppliers in the field of distributed generation is IEEE 1547 standard. This standard was prepared in year 2003, and after that, was followed by different modifications and supplementary parts. This standard is for interconnecting distributed resources with the electric utility grid. Authors of Refs. [59–62] presented a brief description of this standard. Vaziri et al. [60] presented the key standards that regulate the interconnection process, and all requirements needed for that. The report prepared by Narragansett Electric Company [62] presented in detail the whole procedure to connect a distribution generator source to a utility network. Moreover, the report lists different interconnection requirements needed to make the interconnection. These requirements include the design considerations (voltage, frequency, noise and harmonics), protection requirements, operating requirements and insurance requirements.

Regulating barriers are issues that authors of [63] addressed in their report. They summarized these barriers in their report and divide them to technical, economic and environmental barriers. Martel and Turcotte [59] concluded that despite the work done to develop national and international consensuses, more is needed in order to facilitate the deployment of the distributed generation in Canada. Vaziri et al. [60] concluded that further studies will be needed as more distributed generation resources get interconnected to utility grids, while Ropenus et al. [58] concluded that different strategies shall be adopted to promote electricity from distributed generation that depends on renewable energy sources and combined heat and power. These strategies are relevant to feed-in-tariff, various network regulations, incentive regulations and economic standards.

7. Conclusions

Integrating renewable energy sources with a backup source to supply a load is recognized as a viable solution for different applications. This system achieves the best use of operating characteristics for different components at higher efficiencies, lower pollutant emissions and higher reliability. If this backup source is microturbine, these merits will be more obvious because it produces electricity and heat, and generally uses fuel with less pollutant. This hybrid system overcomes any challenges of renewable source fluctuations, and in most cases, minimizes a need for an energy storage system. Connecting this hybrid system as a distributed generation with the grid utility will surely enhance the benefits. This will realize the substantial reliability and economic benefits and serves all relevant parties. However, more research and development regarding modeling, design, optimization and standards are still needed.

This paper has reviewed the adoption of this technology, its deployment, barriers that it faces and recommendations through reviewing different research work regarding these different issues. Modeling of the microturbine is carried out on both the dynamic and steady state behavior. Most of the reviewed works focuses on dynamic behavior modeling of the microturbine in its standalone operation, or with other sources within a hybrid system. The commonly used model of the microturbine which models its dynamic behavior is called GAST model. This model takes into account speed control, fuel control and/or temperature and acceleration controls. The results of simulation of this model illustrate its applicability to simulate the operation accurately. Other similar models are used by other authors. Economical (fuel consumption) modeling can be found in some of research works, and in their economical modeling of the microturbine, the authors depend on the curves prepared by the manufactures. These curves differ between manufacturers. In these curves, some manufactures relate the efficiency to output power, while others relate fuel consumption to output power. These curves are microturbine specific. An approximate generalized economic model can be derived from these curves. This is true, since after revision of curves of different manufactures, and for different ratings from the same manufacturer, it seems that to a large extent, they behave similarly, and it is something worth looking into in future works. According to the review carried out in this paper, the microturbine has attractive features from different point of views and in different modes of operation, which encourages investors, utilities, and consumers to adopt this technology. Another general conclusion that different research works in this review have pointed out is that utilizing microturbine with PV panels as a hybrid system will enhance the PV penetration level as a source for different applications. Research that supports the development of new technology for implementing microturbines in distributed generation, addresses the barriers that are associated with this implementation, increases efficiency and reliability, reduces costs and emissions and develops national and international standards and regulations.

The following comments were highlighted from different reviewed studies:

- There is still a need for a safe, efficient, low cost and clear process for interconnection of the microturbine to grid utility.
- There is still a need for the regional requirement for products to meet market needs.
- Including a carbon tax that targets carbon rich fuels to the pricing of energy can increase the deployment of microturbine applications.
- Using an absorption chiller to recover waste heat from microturbine will improve the overall efficiency of the system, and
- More incentives to natural gas distribution companies will encourage more investments in microturbine technology.

Acknowledgment

The authors would like to acknowledge the Ministry of Higher Education of Malaysia and The University of Malaya, Kuala Lumpur, Malaysia for the financial support under UM.C/HIR/MOHE/ENG/21 (D000021-16001).

References

[1] El-Khattam W, Salama MMA. Distributed generation technologies, definitions and benefits. Electric Power Systems Research 2004;71:119–28.
[2] Tikkisetty T, Gutta B. Modeling and simulation of micro turbine based DG system feeding vector controlled induction motor (VCIM) drive and other static loads. International Journal of Advanced Engineering Sciences and Technologies 2011;9:289–93.
[3] Jahani R, Malekshah AS, Nejad HC, Araskalaei AH. Applying a new advanced intelligent algorithm for optimal distributed generation location and sizing in radial distribution systems. Australian Journal of Basic and Applied Sciences 2011;5:642–9.
[4] Mohamed A, Nizam M, Salam AA. Performance evaluation of fuel cell and microturbine as distributed generators in a microgrid. European Journal of Scientific Research 2009;30:554–70.
[5] Nikkhajoei H, Iravani MR. Modeling and analysis of a micro-turbine generation system. Power engineering society summer meeting, 2002 IEEE. 2002. 167-169.
[6] Gaonkar DN, Patel RN. Modeling and simulation of microturbine based distributed generation system. Power India conference, 2006 IEEE 2006. p. 5.
[7] Hwang Y. Potential energy benefits of integrated refrigeration system with microturbine and absorption chiller. International Journal of Refrigeration 2004;27:816–29.
[8] Wang W, Cai R, Zhang N. General characteristics of single shaft microturbine set at variable speed operation and its optimization. Applied Thermal Engineering 2004;24:1851–63.

[9] Belmonte S, n˜ez VN, Viramonte JG, Franco J. Potential renewable energy resources of the Lerma Valley, Salta, Argentina for its strategic territorial planning. Renewable and Sustainable Energy Reviews 2009;13:1475–84.
[10] Zhu Y, Tomsovic K. Development of models for analyzing the load-following performance of microturbines and fuel cells. Electric Power Systems Research 2002;62:1–11.
[11] Bruno JC, Ortega-López V, Coronas A. Integration of absorption cooling systems into micro gas turbine trigeneration systems using biogas: case study of a sewage treatment plant. Applied Energy 2009;86:837–47.
[12] Kalantar M, Mousavi SMG. Dynamic behavior of a stand-alone hybrid power generation system of wind turbine, microturbine, solar array and battery storage. Applied Energy 2010;87:3051–64.
[13] Thornton A, Monroy CR. Distributed power generation in the United States. Renewable and Sustainable Energy Reviews 2011;15:4809–17.
[14] Saha AK, Chowdhury S, Chowdhury SP, Crossley PA. Modeling and performance analysis of a microturbine as a distributed energy resource. IEEE Transactions on Energy Conversion 2009;24:529–38.
[15] Pilavachi PA. Mini- and micro-gas turbines for combined heat and power. Applied Thermal Engineering 2002;22:2003–14.
[16] Poore WP, Stovall TK, Kirby BJ, Rizy DT, Kueck JD, Stovall JP. Connecting distributed energy resources to the grid: their benefits to the DER owner/customer, other customers, the utility, and society. Ornl/TM-2001/290. Tennessee: Oak Ridge National Laboratory; 2001 p. 55.
[17] Moya M, Bruno JC, Eguia P, Torres E, Zamora I, Coronas A. Performance analysis of a trigeneration system based on a micro gas turbine and an air-cooled, indirect fired, ammonia–water absorption chiller. Applied Energy 2011;88:4424–40.
[18] McDonald CF. Recuperator considerations for future higher efficiency microturbines. Applied Thermal Engineering 2003;23:1463–87.
[19] Salomóna M, Savolab T, Martina A, Fogelholmb C-J, Franssona T. Small-scale biomass CHP plants in Sweden and Finland. Renewable and Sustainable Energy Reviews 2011;15:4451–65.
[20] McDonald CF. Low-cost compact primary surface recuperator concept for microturbines. Applied Thermal Engineering 2000;20:471–97.
[21] Hussein DN, El-Sayed MAH, Attia HA. Modeling and simulation of distributed generation (DG) for distribution systems load flow analysis. In: The 11th international middle east power systems conference (MEPCON'2006) 2006. p. 285–291.
[22] Medrano M, Brouwer J, McDonell V, Mauzey J, Samuelsen S. Integration of distributed generation systems into generic types of commercial buildings in California. Energy and Buildings 2008;40:537–48.
[23] Kaikko J, Backman J. Technical and economic performance analysis for a microturbine in combined heat and power generation. Energy 2007;32:378–87.
[24] Goldstein L, Hedman B, Knowles D, Freedman SI, Woods R, Schweizer T. Gas-fired distributed energy resource technology characterizations. National Renewable Energy Laboratory; 2003 p. 226.
[25] Naik-Dhungel N. Biomass combined heat and power catalog of technologies. U. S. Environmental Protection Agency Combined Heat and Power Partnership. 2007. 123.
[26] Review of combined heat and power technologies—workshop on combined heat and power development in Virginia. Virginia Tech.—Advanced Research Institute; 2003. p. 11.
[27] Akorede MF, Hizam H, Pouresmaeil E. Distributed energy resources and benefits to the environment. Renewable and Sustainable Energy Reviews 2010;14:724–34.
[28] Oğuza Y, Üstünb SV, Is Yabanovaa, Yumurtaci M, Güneyc Ir. Adaptive neuro-fuzzy inference system to improve the power quality of a split shaft microturbine power generation system. Journal of Power Sources 2012;197:196–209.
[29] Guda SR, Wang C, Nehrir MHA. Simulink-based microturbine model for distributed generation studies. Power symposium; 2005. In: Proceedings of the 37th Annual North American 2005. p. 269–274.
[30] Bertani A, Bossi C, Fornari F, Massucco S, Spelta S, Tivegna F. A microturbine generation system for grid connected and islanding operation. Power systems conference and exposition; 2004. IEEE PES2004. p. 360–365 vol. 1.
[31] Kumar A, Sandhu KS, Jain SP, Kumar PS. Modeling and control of micro-turbine based distributed generation system. International Journal of Circuits, Systems and Signal Processing 2009;3:65–72.
[32] Li G, Li G, Yue W, Zhou M, Lo KL. Modeling and simulation of a microturbine generation system based on PSCAD/EMTDC. Critical infrastructure (CRIS), 2010 fifth international conference on 2010. p. 6.
[33] Alkhalil F, Colas F, Robyns B. Secant minimizes the cost of fuel and emissions in a power station of small cogeneration multi machines. 1ère Conférence Franco-Syrienne sur les énergies renouvelables (CFSER 2010). 2010. p. 12 pp.
[34] Hernandez-Aramburo CA, Green TC, Mugniot N. Fuel consumption minimization of a microgrid. IEEE Transactions on Industry Applications 2005;41:673–81.
[35] Rahman S, Pipattanasomporn M, Tech V. Modeling and simulation of a distributed generation-integrated intelligent microgrid. Strategic Environmental Research Development Program 2010 p. pp 63.
[36] El-Sharkh MY, Sisworahardjo NS, Uzunoglu M, Onar O, Alam MS. Dynamic behavior of PEM fuel cell and microturbine power plants. Journal of Power Sources 2007;164:315–21.
[37] Uzunoglu M, Onar O, El-Sharkh MY, Sisworahardjo NS, Rahmana A, Alama MS. Parallel operation characteristics of PEM fuel cell and microturbine power plants. Journal of Power Sources 2007;168:469–76.
[38] Rajashekara K. Hybrid fuel-cell strategies for clean power generation. IEEE Transactions on Industry Applications 2005;41:682–9.
[39] Daud A, Ismail MS. Design of isolated hybrid systems minimizing costs and pollutant emissions. Renewable Energy 2012;44:215–24.
[40] Martín JIS, Zamora I, Martín JJS, Aperribay V, Eguia P. Hybrid fuel cells technologies for electrical microgrids. Electric Power Systems Research 2010;80:993–1005.
[41] Komatsu Y, Kimijima S, Szmyd JS. Performance analysis for the part-load operation of a solid oxide fuel cell–micro gas turbine hybrid system. Energy 2010;35:982–8.
[42] Mousavi SMG. An autonomous hybrid energy system of wind/tidal/microturbine/battery storage. Electrical Power and Energy Systems 2012;43:1144–54.
[43] Pearce JM. Expanding photovoltaic penetration with residential distributed generation from hybrid solar photovoltaic and combined heat and power systems. Energy 2009;34:1947–54.
[44] Caisheng W, Colson CM, Nehrir MH, Jian L. Power management of a stand-alone hybrid wind-microturbine distributed generation system. Power Electronics and Machines in Wind Applications, IEEE 2009:7 PEMWA2009.
[45] Mohamed FA, Koivo HN. Multiobjective optimization using mesh adaptive direct search for power dispatch problem of microgrid. Electrical Power and Energy Systems 2012;42:728–35.
[46] Smolen S, Budnik-Rodz M. Economical analysis of energy conversion and use by cogeneration systems with microturbines. In: Proceedings of the third iasme/wseas international conference on heat transfer, thermal engineering and environment. Greece; 2005. p. 373–376.
[47] Aguiar ABM, Pinto JOP., Nogueira LAH. Modeling and simulation of natural gas microturbine for residential complexes. In: Proceedings of the world congress on engineering and computer science; 2007. San Francisco 2007. p. 4.
[48] Mazandarani A, Mahlia TMI, Chong WT, Moghavvemi M. Fuel consumption and emission prediction by Iranian power plants until 2025. Renewable and Sustainable Energy Reviews 2011;15:1575–92.
[49] Shekarchian M, Moghavvemi M, Mahlia TMI, Mazandarani A. A review on the pattern of electricity generation and emission in Malaysia from 1976 to 2008. Renewable and Sustainable Energy Reviews 2011;15:1575–92.
[50] Colombo LPM, Armanasco F, b OP. Experimentation on a cogenerative system based on a microturbine. Applied Thermal Engineering 2007;27:705–11.
[51] Partnership USEPA-CHaP. Catalog of CHP technologies. CHP comined heat and power partner ship; 2008. p. 139.
[52] Canova A, Chicco G, Genon G, Mancarella P. Emission characterization and evaluation of natural gas-fueled cogeneration microturbines and internal combustion engines. Energy Conversion and Management 2008;49:2900–9.
[53] Qian K, Zhou C, Yuan Y, Shi X, Allan M. Analysis of the environmental benefits of distributed generation. Power and energy society general meeting—conversion and delivery of electrical energy in the 21st century; 2008 IEEE 2008. p. 5.
[54] Gomes EEB, MARd Nascimento, Lora EES, Pilidis P, Haslam A. Performance evaluation and case studies of microturbines fuelled with natural gas and diesel. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 2004:599–607.
[55] Frías P, Gómez T, Cossent R, Rivier J. Improvements in current European network regulation to facilitate the integration of distributed generation. Electrical Power and Energy Systems 2009;31:445–51.
[56] Cossent R, mez G, PabloFrías. Towards a future with large penetration of distributed generation: is the current regulation of electricity distribution ready? Regulatory recommendations under a European perspective Energy Policy 2009;37:1145–55.
[57] Vaessen P, Thielens D. Policy and incentives on distributed generation. Leonardo Energy 2007:10.
[58] Ropenus S, Jacobsen HK, Schröder ST. Network regulation and support schemes—how policy interactions affect the integration of distributed generation. Renewable Energy 2011;36:1949–56.
[59] Martel S, Turcotte D. Review of distributed generation product and interconnection standards for Canada. IEEE electrical power conference, October 25–26; 2007. Montreal, Quebec, Canada 2007. p. 6.
[60] Vaziri M, Vadhva S, Oneal T, Johnson M. Distributed generation issues, and standards. Information reuse and integration (IRI); 2011. IEEE international conference on 2011. p. 439–443.
[61] Basso TS, DeBlasio R. IEEE 1547 series of standards: interconnection issues. IEEE Transactions on Power Electronics 2004:1159–62 September.
[62] Standards for connecting distributed generation. The Narragansett Electric Company; 2007. p. 80.
[63] Schwartz L. Distributed generation in Oregon: overview, regulatory barriers and recommendations. Public Utility Commission 2005:61.